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Dispersion compensation and gain flattened for a wavelength division multiplexing system by using chirped fiber gratings in an erbium-doped fiber amplifier

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Abstract

A new technique, using chirped fiber gratings (CFGs) with different dispersions and center frequencies to reflect the different channel pulses at different positions, is proposed to compensate for the accumulated dispersions and flatten the signal gain of the erbium-doped fiber amplifier (EDFA) in a wavelength division multiplexing (WDM) system. A numerical example of the gain flattened and dispersion compensation for four channel multiplexed signals in the 1544–1556 nm wavelength region is shown. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Erbium-doped fiber amplifier; Chirped fiber grating; Wavelength division multiplexing

1. Introduction

Wavelength division multiplexing (WDM) technique, combined with an erbium-doped fiber amplifier (EDFA), has become very attractive for high-speed and high-capacity optical transmission systems. However, the inherent wavelength dependence of the gain, causing unequal optical signal powers among the WDM channels in cascaded EDFA and limiting the available optical bandwidth, degrades the performance of optically amplified transmission systems and networks. In order to overcome this difficulty, several approaches have been proposed to broaden and flatten the gain bandwidth, such as high-concentration alumina (Al) co-doped EDFAs [1,2], erbium-doped fluoride fiber amplifiers [3], and gain equalizing optical filter: the Mach–Zehnder optical filter [4], the acousto-optical filter [5], and the long-period fiber-grating filter [6]. Because these filters function primarily as a wavelength-dependent attenuator, the use of the gain equalizer tends to lower the efficiency and the output power. We have proposed a flattened fiber amplifier by using a fiber-Bragg grating without sacrificing the power conversion efficiency [7].

The other barrier toward realization of WDM systems is the fiber chromatic dispersion which limits the bit rate by temporally spreading the transmitted optical pulses. One method to reduce the effect of dispersion is to use a dispersion-compensated fiber (DCF). An alternative to the DCF is the chirped fiber grating (CFG) which is polarization insensitive, compact, low-loss, and relatively easy to produce. Several experiments and theoretical investigations have shown their potential for dispersion compensation [8–11]. As well, the sign of the dispersion in reflection mode is easily controlled. In this paper, we propose a new technique employing CFGs to compensate for the pulse dispersion and flatten the signal gain of a WDM system simultaneously. CFGs with different center frequencies can be written at different positions of the EDFA to reflect the signal of different channels. By designing the dispersion of the reflection mode of each CFG, the accumulated disper-

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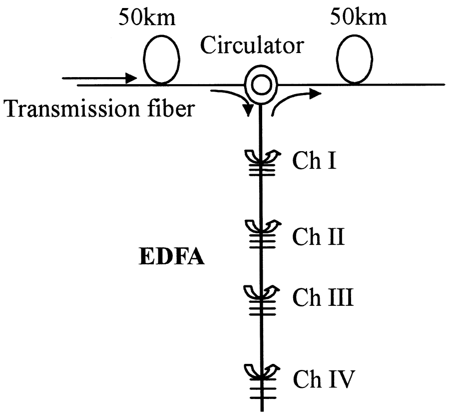

Fig. 1. The schematic diagram of a WDM system.

sion of the transmission fiber is compensated for each channel. We optimize the written position of each CFG in the EDFA, the pulses of different channels can obtain equal gain in the backward direction. The schematic diagram of a WDM transmission system with 50 km amplifier spacing is shown in Fig. 1.

2. Theory

The propagation equation of a linear pulse in a single-mode fiber can be described as:

$$i\frac{\partial U}{\partial z}-\frac{1}{2}\beta_2\frac{\partial^2 U}{\partial \tau^2}-i\beta_3\frac{\partial^3 U}{\partial \tau^3}=-\frac{i}{2}\alpha U \tag{1}$$

where U is the electric field envelope, α is the fiber loss, β_2 and β_3 represent the second- and third-order dispersion, respectively. The transmission fiber has a loss of 0.22 dB/km and zero dispersion wavelength of 1550 nm. The second-order dispersions of channel I (1544.0 nm), II (1548.0 nm), III (1552.0 nm) and IV (1556.0 nm) are 0.66, 0.22, -0.22, and -0.66 $\mathrm{ps}^2/\mathrm{km}$, respectively.

The EDFA can be modeled as a homogeneously broadened two-level system. The spectra of the absorption cross-section (σ_a) and emission cross-section (σ_e) of the Al co-doped EDFA are shown in Fig. 2. The amplified spontaneous emission noises (ASEN) are assumed to be the optical beams of effective frequency bandwidth $\Delta\nu_k$ centered at the wavelength $\lambda_k=c/\nu_k$ to resolve the ASEN spectrum. Under the steady-state condition, the equations to describe the spatial development of the pump power (P_P), signal power (P_s), and ASEN power (P_k, $k=1,\ldots,N$) in the EDFA can be written as:

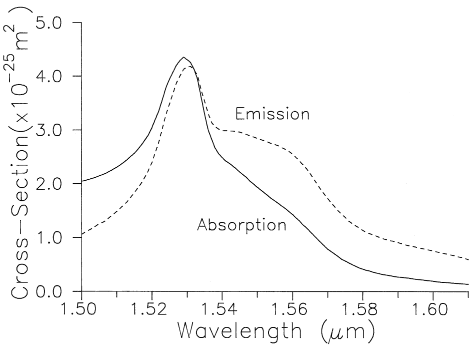

Fig. 2. The absorption cross-section and emission cross-section of an Al co-doped EDFA.

$$u^{\pm}\frac{\mathrm{d}P_P^{\pm}}{\mathrm{d}z}=(\sigma_{ep}N_2-\sigma_{ap}N_1)\Gamma_P P_P^{\pm} \tag{2}$$

$$u^{\pm}\frac{\mathrm{d}P_s^{\pm}}{\mathrm{d}z}=(\sigma_{es}N_2-\sigma_{as}N_1)\Gamma_s P_s^{\pm} \tag{3}$$

$$u^{\pm}\frac{\mathrm{d}P_k^{\pm}}{\mathrm{d}z}=(\sigma_{ek}N_2-\sigma_{ak}N_1)\Gamma_k P_k^{\pm} + 2\sigma_{ek}N_2\Gamma_k h\nu_k\Delta\nu_k-\alpha_{iP}P_k^{\pm} \tag{4}$$

where N_1 and N_2 are the population densities of the ground level and metastable level, σ_{ej}, σ_{aj}, Γ_j, α_P, and $h\nu_j$ are the emission cross-section, absorption cross-section, confinement factor, intrinsic fiber loss, and photon energy, respectively. The superscript ($\pm$) designates the optical beam propagating along $\pm z$ direction and $u^{\pm}=\pm 1$. The coupled Eqs. (2)–(4) are numerically solved with the absorption cross-section (σ_a) and emission cross-section (σ_e) given in Fig. 2. Because the gain is sensitive to the pump wavelength within the 980-nm pump band [12], the 1480-nm pump wavelength λ_p is used and the EDFA length is 10 m. The pump powers are launched into the amplifier at $z=0$ and L bidirectionally. We use 4401 points to sample the AZEN spectrum, which corresponds

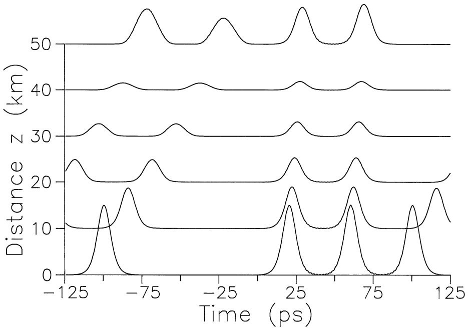

Fig. 3. Without the CFG, the power evolution of four channel linear pulses along 50 km transmission.

to the spacing of $\Delta\lambda = 0.025$ nm. The reflectivity of the CFG can be calculated from the coupled-mode equations:

$$\frac{\mathrm{d}A^+}{\mathrm{d}z} = \kappa(z)\exp\left[-j\int_o^z B(z')\mathrm{d}z'\right]A^-, \tag{5}$$

$$\frac{\mathrm{d}A^-}{\mathrm{d}z} = \kappa(z)\exp\left[j\int_o^z B(z')\mathrm{d}z'\right]A^+, \tag{6}$$

where A^+ and A^- are the amplitudes of the forward and backward propagating modes along the z direction, $\kappa(z)$ is the coupling coefficient and varies along the grating as:

$$\kappa(z) = \kappa_0 \exp(-50z^2/L^2), \quad -L/2 < z < L/2 \tag{7}$$

where κ_0 is the maximum coupling coefficient at $z = 0$ and L is the length of the grating. In general, the gain is smaller than 15 dBm and the pulse width is longer than 5 ps for optical communication systems, the saturation and dispersion of the gain can be neglected in the EDFA [13]. The operation of the EDFA cannot affect the resonant frequency of the fiber gratings. $B(z)$ represents the phase mismatch of the grating and is given by:

$$B(z) = 2\beta - 2\left(\frac{\pi}{\Lambda_0} + F_1\frac{z}{L^2} + F_2\frac{z^2}{L^3}\right) \tag{8}$$

where $\beta = \beta_0 + \delta\beta$ is the propagation constant and β_0 is the propagation constant of central wavelength, $\Lambda_0 = \lambda_0\bar{n}/2 = \pi/\beta_0$ is the grating period at $z = 0$, λ_0 is the central wavelength of carrier waves and $\bar{n}$ is the mode index, F_1 and F_2 are the chirped coefficients. We can adjust the parameters of CFGs to obtain the desirable dispersion.

3. Numerical results and discussion

We demonstrate a four channel WDM transmission system using linear return-to-zero optical pulses of 10-ps pulse width. Without the CFG, Fig. 3 shows the power evolution of four channel linear pulses along 50 km transmission. At $z = 0$, the pulses from right to left belong to channel I, II, III, IV, subsequently. It is seen that the pulses are broadened due to the group-velocity dispersion. The accumulated dispersions are 33, 11, -11 and -33 ps^2 for channels I, II, III, and IV, respectively. Therefore, the pulses of channels I and IV broaden more severely than channels II and III. It is noticed that the gains decrease from channel I to channel IV. To compensate for the accumulated dispersion of each channel, we design CFGs with different center frequencies and parameters for different dispersion compensations. The third-order dispersion of the fiber is positive. We can adjust the parameter F_2 of Eq. (8) to induce negative third-order dispersion of CFG. Thus, the third-order dispersion of the transmission link can be reduced. The gain can be flattened by the CFGs written at different positions of the EDFA. The optimum written position of each CFG along the EDFA for channels I, II, III and IV are 8.6, 8.9, 9.1 and 9.4 m, respectively. Thus, the amplifying length for channel I, II, III and IV are 17.2, 17.8, 18.2 and 18.8 m, respectively. By using the set of CFGs written at optimum position, Fig. 4 shows the power evolution of four channel pulses along 50 km transmission. The output power of each channel pulse is the same, and the pulsewidth is recovered. Therefore, the method can be used in an in-line amplifier to compensate the accumulated dispersion and flatten the channel gain in a WDM system.

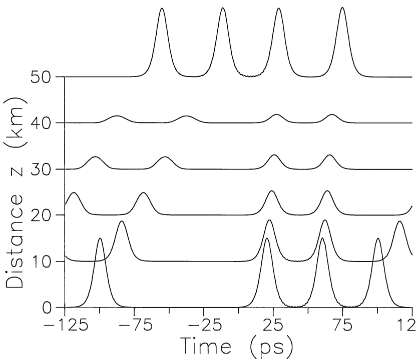

Fig. 4. With CFGs in EDFA, the power evolution of four linear channel pulses along 50 km transmission.

4. Conclusion

A dispersion compensation and gain flattened method in EDFAs has been proposed for WDM systems by using CFGs. We have designed CFGs to compensate for the pulse dispersion and optimize the written positions of the CFGs to achieve the maximum flat gain. The optical amplification and the written positions of the fiber gratings should be considered simultaneously to optimize the performance of the EDFA.

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